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Coronagraphic Imaging: *Keck II* AO and *HST* ACS Compared

Paul Kalas[1]

Astronomy Department, University of California, Berkeley, CA 94720

David Le Mignant

W. M. Keck Observatory, Kamuela, HI 96743

Franck Marchis[1] and James R. Graham[1]

Astronomy Department, University of California, Berkeley, CA 94720

Abstract. Coronagraphic imaging reduces PSF wings by 0.6 mag using Keck adaptive optics in the NIR, and 1.5 mag using ACS in the visible. The PSF suppression attained is roughly comparable for the two instruments. Future work should test the relative contrast gains from PSF subtractions.

1. Introduction

High contrast imaging is necessary to search for and study sub-stellar objects and debris disks surrounding bright stars. Here we compare the performance of coronagraphs used with ground-based adaptive optics (AO) systems to those implemented in *HST* science cameras. The following data are used in the present investigation:

1. With *Keck II* (10 m) AO, we used the coronagraphic mode of the NIRC2 science camera (1024×1024 InSb array). NIRC2 has 10 focal plane occulting spots between 100 mas and 2000 mas diameter, five selectable pupil plane stops, and three selectable plate scales. The $V = 8.8$ star HD 162052 was observed at K', with a 300 mas focal plane mask, a pupil plane mask matched to the telescope pupil (large hexagonal), 120 sec cumulative integration time, and with $0.01''$/pix plate scale. Measured Strehl ratios are S$\sim$50%.

2. For *HST* ACS, we adopted the performance specifications for the F606W filter given in the *ACS Instrument Handbook for Cycle 12* Version 3.0. John Krist also supplied us with the F606W coronagraphic images of Arcturus shown in Chapter 5 of the *ACS Instrument Handbook* (offspot and onspot, with the High Resolution Channel Lyot mechanism in place).

2. PSF Differences

In general, PSFs have static and temporal characteristics, and are composed of both scattered light (the seeing halo) and diffracted light (the Airy disk). The encircled energies of the *Keck* AO and the *HST* ACS data are shown in Figure 1. *Keck* AO produces near diffraction-limited central cores (FWHM = 54 mas), but the uncorrected atmosphere contributes a scattered seeing halo beyond $0.1''$ radius ($2.5\lambda/D$) that contains $\sim$40% of the light.

A coronagraph should have the following effect on the PSF:

[1]Center for Adaptive Optics, University of California, Santa Cruz, CA 95064

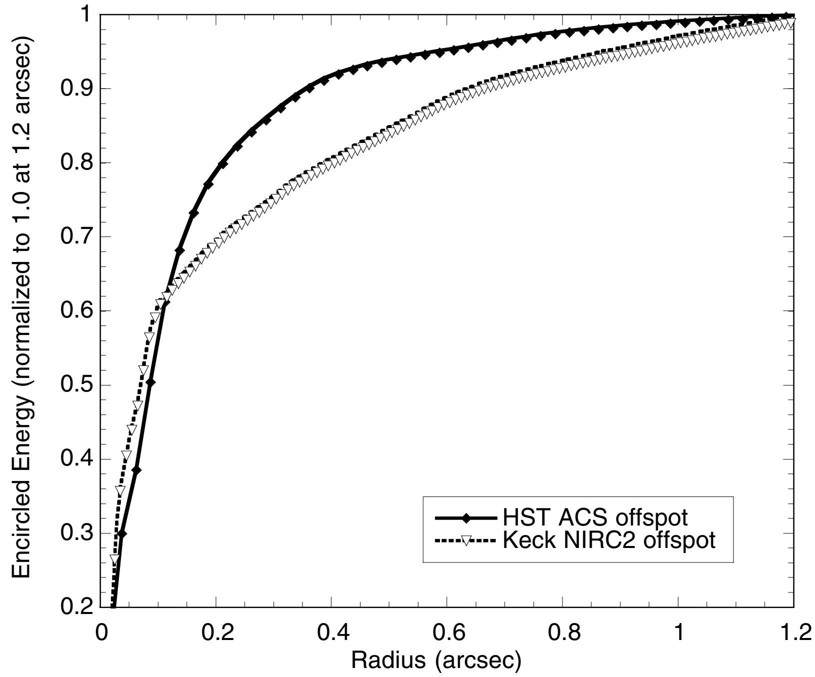

Figure 1. Encircled energies for the stars used to test coronagraph performance, before occultation by a focal plane occulting mask.

- Light scattered into the seeing halo by the atmosphere or by the Optical Telescope Assembly (OTA) is not suppressed.
- Scattered light within the science camera is suppressed because the PSF core is absorbed by the focal plane occulting mask.
- Diffracted light due to the OTA is suppressed, depending on the sizes of the Lyot stop *and* the occulting spot. The larger the occulting spot, the more light is pushed to the edges of the pupil plane image, which is then masked by the Lyot stop.

Based on these principles, the a priori expectation is that the ACS coronagraph will further diminish the intensity of the PSF wings shown in Figure 1 because the PSF is dominated by diffraction. Ground-based, AO coronagraphic data should demonstrate only modest improvement over a non-coronagraphic observations because the seeing halo is dominated by atmospheric scattered light.

3. Coronagraph Suppression

Figure 2 is made by taking the median azimuthal value for each occulted PSF as a function of radius, and converting it to a relative magnitude based on the peak intensity of the star in an unocculted image. We find that the coronagraph suppresses the AO PSF wings by a median value of 0.6 mag in the range $0.2'' - -1.2''$ radius. Thus the suppression of instrumental and diffracted light by the coronagraph gives a somewhat unexpected contrast gain for AO images. The ACS coronagraph suppresses the PSF by a median value of 1.5 mag in the range $1.0'' - -3.0''$ radius.

Overall, the differences between *HST* and *Keck* when comparing the occulted (spot) or unocculted (offspot) PSFs are not significant. Clearly the region within $1''$ radius of the star is accessible with *Keck* AO, whereas the large size (radius $0.9''$) of the smallest ACS occulting spot prevents coronagraphic imaging of the sub-arcsecond region. Recently detected objects follow an envelope

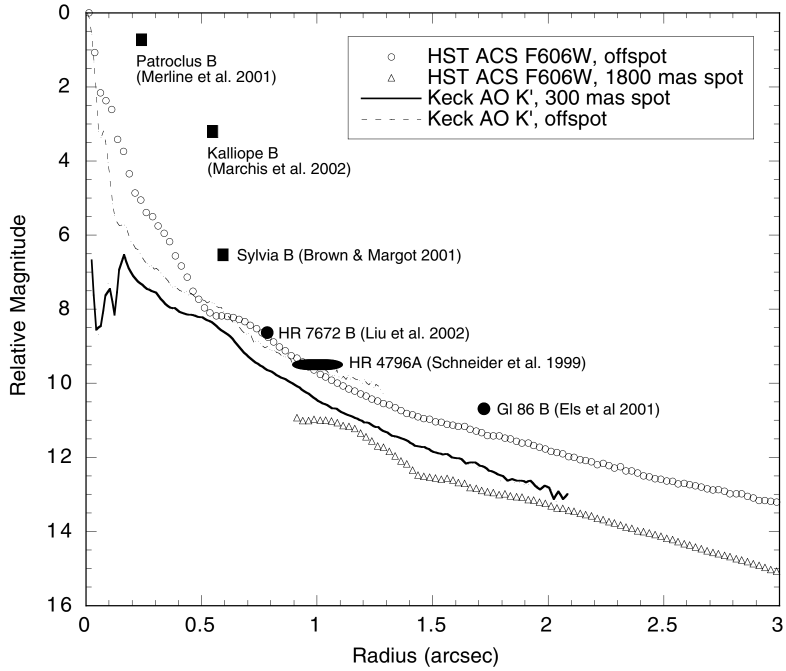

Figure 2. Radial PSF intensity normalized relative to the peak intensity and converted to relative magnitude. Solid circles are sub-stellar objects, solid ellipses are circumstellar disks, and solid squares are asteroidal companions discovered by direct observations with AO systems at *Lick*, *Gemini*, and *Keck*.

just above the PSF curves, indicating that, to first order, a simple radial plot of the PSF corresponds to detection limits.

4. Detectability Simulations

Ultimately the sensitivity of *HST* and *Keck* should be tested by simulating the science objects and working through a variety of observing modes and data reductions (e.g., Kalas & Jewitt 1996, Schneider et al. 2001). A crucial step is subtraction of the PSFs shown in Figure 2 by either self-subtraction after a field roll, or by observing a nearby reference PSF contemporaneously. Because the *Keck* telescope has an alt-az mount that produces field rotation, we are presently testing the efficacy of roll deconvolution from the ground.

For the present investigation, we merely insert a model dust disk into the coronagraphic PSFs without any further data reduction. The model disk is described in Kalas & Jewitt (1996). We fix the disk inclination (73°), central hole radius ($1''$) and peak surface brightness (12 mag arcsec^{-2}), to correspond to the *HST* NICMOS image of HR 4796A (Schneider et al. 1999). The main difference is that the model has no fixed outer extent, whereas the real HR 4796A disk is a confined ring. Figure 3 shows that the ACS coronagraph would detect the dust scattered light if the disk were in fact extended rather than confined. In addition to detecting the outer disk, *Keck* AO reveals the central hole in the dust distribution.

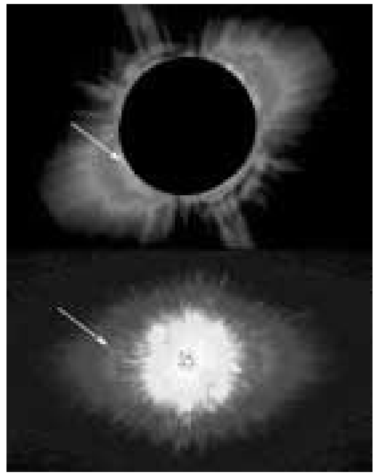

Figure 3. Model HR 4796-like disk inserted into the ACS occulted PSF at PA=135°(top) and into the *Keck* AO PSF at PA = 90°(bottom) . The normal PSF shows an azimuthally symmetric halo, whereas the distortion evident here is due to the circumstellar disk. Arrows designate the brightest portion of the disk within which a central disk hole is present.

5. Conclusions and Future Directions

Coronagraphic imaging reduces the PSF wings by 0.6 mag using *Keck* AO in the NIR, and 1.5 mag using the ACS coronagraph in the visible. In circumstellar regions where these tests overlap, the occulted and unocculted PSF wings show roughly comparable sensitivity for *Keck* AO and *HST*.

Ground-based AO has the advantage over *HST* ACS in imaging circumstellar regions within $1''$ radius. The *HST* NICMOS coronagraph has a smaller occulting spot than ACS, but imaging is still limited to $\sim 0.6''$ radius (Schneider et al. 1999). High-order AO systems will further improve the ground-based capability of imaging the sub-arcsecond circumstellar region (Sivaramakrishnan et al. 2001, Lloyd et al. 2001).

The results shown here have a limited scope. Future work must test the sensitivity gains attained with PSF subtractions and longer integration times. Comparisons of ground-based AO to *HST* NICMOS and STIS coronagraphic data are also necessary.

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References

Brown, M. E. & Margot, J. L. 2001, IAUC 7588

Els, S. G., Sterzik, M. F., Marchis, F., Pantin, E., Endl, M. & Kuerster, 2001, A&A, 370, L1

Kalas, P. & Jewitt, D. 1996, AJ, 111, 1347

Liu, M. C., Fischer, D. A., Graham, J. R., Lloyd, J. P., Marcy, G. W., & Butler, R. P. 2002, ApJ, 571, L519

Lloyd, J. P., Graham, J. R., Kalas, P., et al. 2001, SPIE, 4490, 290

Marchis, F., Descamps, P. , Hestroffer, D., et al. 2002, submitted to Icarus

Merline, E. J., Close, L. M., Siegler, N., et al. 2001, IAUC 7741

Pavlovsky, C., et al. 2002, *ACS Instrument Handbook for Cycle 12* Version 3.0 (Baltimore: STScI)

Schneider G., Becklin, E. E., Smith, B. A., Weinberger, A. J., Silverstone, M., & Heines, D. C. 2001, AJ, 121, 525

Schneider, G., Smith, B. A., Becklin, E. E., et al. 1999, ApJ, 513, L127

Sivaramakrishnan, A., Koresko, C. D., Makidon, R. B., Berkefeld, T., & Kuchner, M. J. 2001, ApJ, 552, 397